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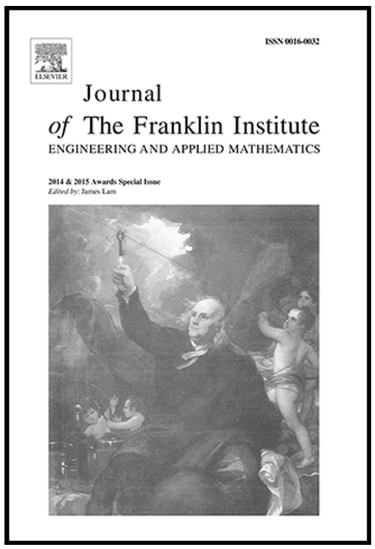

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A Cost-effective Wireless Network Migration Planning Method Supporting High-security Enabled Railway Data Communication Systems

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Abstract

As a typical railway Cyber-physical System (CPS), radio-based train control systems have been playing an increasingly important role in rail transit. The engaged network, Global System for Mobile Communications for Railway (GSM-R), which is an out-dated wireless communication technology, will be decommissioned due to diminishing support from industry, and a new generation successor, e.g. Long-Term Evolution (LTE), is urgently required to replace the current network. The radio-based train control systems must be safetycritical, which relies on a high-security Data Communication System (DCS). In this paper, a novel wireless network migration methodology in DCS is proposed. By using this methodology, the high-security required DCS performance in radio-based train control systems is maintained and the network migration cost, e.g. the used number of base station (BS), is reduced when updating the GSM-R to LTE.

Keywords: Railway cyber-physical System (CPS), wireless communication,

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data communication systems (DCS), network migration, base station (BS), deployment optimisation.

1. Introduction

The radio-based train control systems, especially in high-speed railways (HSR), utilise modern wireless communication technologies, computing and sensing capabilities to meet the increasing demands for rail transit, in terms of better reliability, higher capacity and low safety risk. The systems incorporate the cyber networks (e.g. train-to-wayside wireless communication, computer-based interlocking) with the physical elements (e.g. movement in space and real-time interfacing with the physical environment, including train positioning and speed sensing), thus forming Cyber-Physical Systems (CPSs)[1]. Wireless connections are central to the design of advanced CPSs, in which communication links must meet stringent requirements on throughput, latency, range and providing high levels of reliability [2]. As the train relies on the wireless communication based Data Communication System (DCS) to transmit the Train Data (TD) to conduct the train control [3], including the exact position, speed and direction of every running train, and to deliver the generated moving authorities (MA) to the corresponding trains on a timely basis, a high-security enabled DCS is very significant for this kind of CPSs.

In Europe, the European Train Control System (ETCS) has been designed to replace old generation railway signalling systems. There are 4 levels specified in ETCS (from level-0 to level-3), the most advanced level achievable is ETCS-2, which is a radio-based system. In ETCS-2, by employing Global System for Mobile Communications for Railway (GSM-R), continuous data transmissions are carried out between the Train Onboard Unit (OBU) and the wayside Radio Block Centre (RBC), which enables the zone controller to know the TD timely. Since the system standard was finalized in 2000, GSM-R based train control systems have been used extensively, including in China, India, Russia and the United States. According to the report by the International Union of Railways,

over 70000 kilometers of track are covered by GSM-R across the world. The typical structure of a radio-based train control system is shown in Figure 1. Radio-based train control systems use distributed network, whereby a number of RBC are deployed along the rail with connecting multiple wayside terminals (e.g. base stations (BS) in GSM-R or Evolved Node B (eNodeB) in Long-term Evolution (LTE)). Each of the wayside terminals has a cell range, when a train runs in a cell range, the wireless connection is built and data exchange between the train and the RBC occurs. To assure the train-to-wayside connection is continuous, the cell ranges must be seamlessly overlapped.

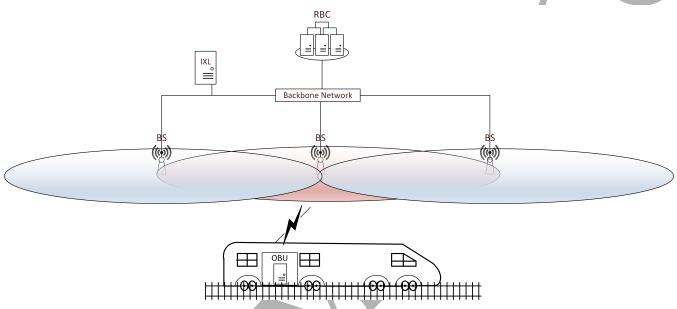

Figure 1: The typical structure of the European Train Control Systems (ETCS)

With the fast development of modern wireless technology, it has been recognized that GSM-R, which is an ageing technology, has a number of drawbacks, e.g. low capacity, decreasing number of users and increasing system maintenance cost [4]. In the next generation railways, particularly for HSR, communication networks must not only provide dedicated train control data connections, but they also need to offer public broadband communications in order to support other services, e.g. onboard video surveillance, track monitoring, public internet access and online entertainment [5]. All of these services are dependent on a high quality-of-service (QoS), in terms of a higher data rate, shorter transmission latency and lower bit error rate (BER) [6], which are beyond the reach of GSM-R [7]. Moreover, as the industry has announced that the technical support for GSM will be terminated no later than 2025 [8], it is imperative that the railway dedicated wireless network is switched from GSM-R to a new generation

wireless network. Therefore, the insistent demand to migrate the wireless network for railways to a successor technology to GSM-R has long been recognised by all major railway authorities, including the European Rail Agency, which is the railway authority for the European Union.

LTE, which is a type of widely engaged fourth-generation (4G) broadband system [9], is considered as the most likely successor to GSM-R [10]. There are several reasons why LTE is likely to succeed GSM-R. Firstly, compared with second-generation (2G) network systems (e.g. GSM) and the third-generation (3G) network (e.g. Wideband-Code Division Multiple Access, Time Division Synchronous-Code Division Multiple Access and Worldwide Interoperability for Microwave Access), LTE has a much higher bit rate of up to 100 Mbit/s in the downlink and 50 Mbit/s in the uplink. Secondly, compared with the fifth-generation (5G) network, which is still under discussion in the 3rd Generation Partnership Project (3GPP), with the relevant standard due to be released by 2020, LET is a mature technology. Finally, LTE backbones provide support for GSM, which enables an easier migration process [11]. Based on the ERA's idea, the network migration from GSM-R to LTE for Railway (LTE-R) will be implemented in three phases [12]. In the first phase, before the new LTE-R standard is finalised, GSM-R will be still the mainstream for radio-based railway control systems for both newly-built railways and upgraded railways. In the second step, once the LTE-R standard is proposed, LTE-R and GSM-R will co-exist in the DCS until the industry technical support for GSM-R is stopped. During this co-existing period, the GSM-R network will be mainly in charge of transmitting safety-related data (e.g. TD and MA), whilst the LTE-R network will be responsible for non-safety related data (e.g. onboard surveillance and public internet access). Finally, after GSM-R is decommissioned, LTE-R will be employed to transmit both safety and non-safety related data.

The construction and maintenance cost of the wireless network in railways is very substantial [12], therefore, during this network migration, how to protect the existing investment in the network infrastructures will not be a negligible issue. As stated in a report [13], in mainline railways, the cost of the wireless

network takes 40% of the whole budget of building a train control system, which requires over 50,000 US dollars per kilometer to construct [14]. To tackle this challenge, a number of railway network hardware suppliers have announced dual-mode BS, which enables an easy switch between GSM-R and LTE-R. By utilizing this type of BS, the GSM-R based railway network will be capable of migration to a LTE-R based railway network without replacing any hardware modules. For GSM-R, in Europe, the working frequency is 873-880MHz at uplink and 918-925MHz at downlink [15], which provides a cell range around 6-8 km. Unlike the GSM-R, there is no standard spectrum specification for LTE networks. Currently, a number of spectrum chunks, from 450MHz to 5.9 GHz, are used by the civil LTE in different countries. For the upper bands (higher frequency), they can provide larger bandwidth, but result in a shorter distance coverage; on the contrary, lower bands (lower frequency) can benefit from a much bigger cell coverage, but only a low bit rate is enabled. Therefore, no matter what spectrum is chosen by LTE-R, due to the different allocations in spectrum, it is hard to achieve exactly the same cell range for GSM-R and LTE-R. As a result, to implement a successful network migration, the deployment of the dual-mode BS must be well-planned.

In [12], a strategic study on the network migration is presented, however, there is no detailed methodology proposed. A number of studies have been carried out focussing on the deployment planning of BS, or access point (AP) in different networks. For the GSM network, in [14], the BS placement problem in HSR environments has been addressed, and an optimized BS deployment arrangement with reducing cost is proposed, however, in this method, no attention is paid to interference. In addition to [14], in [16], an interference evaluation model and an optimisation methodology to minimise the co-channel interference in the GSM network is presented. In [17], an automatic planning tool for a cellular GSM network in urban areas is presented. In this tool, the *Cost231* model is used to predict the wireless propagation, and detailed urban features are accounted for. For the LTE network, in [18], in order to have a better coverage, the traditional macro cells are overlapped by small cells with reduced dimensions in

the LTE network coverage planning, as with different overlapping approaches, different antenna beamformings are achieved. In [19], a rethinking for the 4G cellular network planning is proposed, in which the essential objectives of designing a cellular network are addressed and a dynamic network planning framework is presented. In [20], an AP deployment optimisation method in Wireless Local Area Networks (WLAN)-based Communication-Based Train Control (CBTC) systems is proposed, and to make this proposed methodology more available in real-world systems, more efficient optimisation search algorithm has been adopted in [21]. There is further literature focusing on AP planning problems in general WLAN systems. In [22] and [23], the optimal AP placement problems for indoor WLAN systems are explored. In other research, the AP placement planning problem in WLAN systems is addressed, together with channel assignment: in [24] [25] [26], one joint and three separate optimization planning methods for both AP placement and channel assignment in indoor WLAN systems are proposed. In some research [27] [28] [29] [30], network power control is adapted to change the UE output power such that it adjusts the cell range. By using this mechanism, the cell range difference between LTE and GSM-R can be compensated. However, as the volume of the adjustable power is limited, if the difference of the cell range is out of reach, a compromised DCS performance of the migrated network will be caused.

The main contribution of this paper is to propose a dedicated network migration methodology in radio-based train control systems. By employing this methodology, an optimized railway communication network can be designed for the future network migration, in terms of seamless radio coverage, less co-channel interference, higher performance and lower cost ensuring maximum protection for the existing investment on network infrastructure. This paper is arranged as follows: Section 2 builds dedicated wireless channel models in railway environments, and some underlying challenges for building a reliable wireless connection are investigated and modelled. In Section 3, the network migration methodology is proposed. In Section 4, a methodology application is presented, an indicative case study is carried out to evaluate the methodology. In Section

5, an integrated test platform is introduced, and the optimized BS deployments are tested. Finally, the conclusion and future work are presented in Section 6.

2. Network Modelling in Communication Systems

In wireless communication networks, the radio frequency carrier with modulated data propagates from the transmitter to the receiver through the wireless channel [31]. In Section 2.1, a brief comparison between GSM-R and LTE is made. To model the wireless channel in the network, an empirical propagation model and the outage probability are proposed in Sections 2.2 and 2.3 respectively. The key parameters used in calculating the outage probability are discussed in Sections 2.4 and 2.5.

2.1. Comparison Between GSM-R and LTE

As two different generation communication networks, there are a number of differences underlying GSM-R and LTE. The system specifications used in GSM-R and LTE are summarized in Table 1.

Table 1: Comparison between GSM-R and LTE-R

Specification	GSM-R	LTE-R
Carrier frequency	900MHz	460MHz-5.9GHz
Duplex mode	FDD	FDD/TDD
Chan. bandwidth	2 KHz	1.4-20 MHz
Modulation	GSMK	QPSK/16QAM
Access scheme	TDMA	OFDMA/SC-FDMA
Peak data rate	9.6 Kbps	150/50 Mbps
Max mobility	500 km/h	500 km/h
Service	Voice/data	Voice/data/video

2.1.1. Carrier frequency

GSM-R uses dedicated a spectrum and the frequency allocation is around 900 MHz. In Europe, the uplink is 873-880 MHz and the downlink is 918-925 MHz,

and in China, the uplink is 885-889 MHz and the downlink is 930-934 MHz. The availability of frequency allocation is much wider for LTE, which gives a number of options for LTE-R. For the frequency-division duplex (FDD) based LTE, the available spectrums are from 460MHz-5.9GHz, for the frequency-division duplex (TDD) based LTE, the available spectrum is from 700MHz-5.9GHz. However, as the high-frequency bands suffer more serious data loss in propagation and lead to a cell range which too small, for the demands of system reliability, middle-to-low frequency bands are more often considered.

2.1.2. Duplex mode

GSM-R uses FDD to implement duplex communication, and one uplink and one downlink carrier are specified in different frequency bands. LTE can either use FDD or TDD. In TDD, users can use the same carrier but in different turns.

2.1.3. Channel bandwidth

The channel spacing in GSM-R is 200 KHz. For different LTE configurations, the channel bandwidth can be 1.4, 3, 5, 10, 15 and 20 MHz.

2.1.4. Modulation

GSM-R uses the Gaussian minimum shift keying (GSMK) to modulate the carrier signal. GSMK is an extension of the minimum shift keying (MSK), by prior application of a Gaussian filter to the data stream, the interference between the adjacent signal carriers is reduced. The main shortcoming of GSMK is the low power efficiency. LTE-R uses rectangular quadrature amplitude modulations (QAM) (e.g. 4QAM, 16QAM and 64QAM). Compared with other modulation schemes, rectangular QAM have high spectral efficiency with a relatively low power assumption.

2.1.5. Access scheme

GSM-R and LTE use different media access schemes to share their channel resource. For GSM-R, time-division multiple access (TDMA) is adopted. By using TDMA, the channel is divided into a number of time slots, and each

channel user transmits the data succession by using their own allocated time slot. For LTE, orthogonal frequency-division multiple access (OFDMA) is applied to manage the channel access for different users. Instead of TDMA, in OFDMA the frequency is divided into different orthogonal subcarriers which are allocated to different users, which enables a good robustness to multipath fading and efficient spectrum usage. For uplink, the data stream is linearly proceeded, which is referred to as SC-FDMA. Modulated symbols are individually transmitted in the series, however, for the downlink, original OFDMA is applied, in which all of the modulated symbols are transmitted at one time.

2.1.6. Peak data rate

The peak data rate of GSM-R is 9.6 Kbps in both the downlink and uplink per connection [32]. For LTE, the theoretical peak data rate of the signal data stream can reach 172 Mbps and 85 Mbps in the downlink and uplink respectively. However, in railway scenarios, the peak data rate of LTE-R is cut to 150 Mbps in downlink and 50 Mbps in uplink at most (when working in a 20 MHz channel bandwidth).

2.1.7. Mobility

GSM-R has been proven to be capable of a maximum speed of 500 km/h. In [33], it is shown that LTE has no problem in serving the train control system under as high as 500 km/h mobility.

2.2. Wireless Channel Modelling

The received signal power is a very important criterion for a reliable wireless connection, which is dependent on a number of factors. By taking all of these factors into account, the link budget of the average received signal power is [34]:

$$P_r[\text{dBm}] = P_t + G_{enb} + G_{ob} - L_{enb} - L_{ob} - L_{PL} + \sigma_{dB} \tag{1}$$

where

- P_r is the received power of at the onboard transmitter;

- P_t is the transmission power of the eNodeB;
- G_{enb} is the antenna gain of the eNodeB;
- G_{ob} is the antenna gain of the onboard transmitter;
- L_{PL} is the propagation path-loss;
- σ_{dB} is random factor caused by the shadowing effects.

Among these factors, path-loss and interference are decided by the propagation channel environment. There are two types of channel model used to describe the radiowave propagation, namely empirical channel models and deterministic channel models [35]. Generally speaking, radiowave propagation can be determinately described by Maxwell equations [36], waveguide models [37] and ray tracing channel models [31]. However, in solving real-world problems which consist of a countless number of elements and many types of material with different electromagnetic properties, precisely implementing deterministic channel models will lead to extremely complex mathematical formulations [38]. Contrasting with the deterministic channel models, empirical channel models describe the radiowave propagation based on observations and measurements alone, which can also achieve a good prediction result with consuming reasonable computation. Due to the accurate prediction result with a moderate computational cost, empirical channel models are widely used in network planning. In the 3GPP standard, the *COST231 HATA* Model [39] is used to predict the path-loss,

$$\begin{aligned} L_{PL}(d)[\text{dBm}] =& (44.9 - 6.55 \times h_{enb}) \times \log_{10}(d) \\ &+ 45.5 + (35.46 - 1.1 \times h_{ob}) \times \log_{10}(f) \\ &- 13.82 \times \log_{10}(h_{ob}) + 0.7 \times h_{ob} + C \end{aligned} \tag{2}$$

where f is the carrier frequency in MHz, h_{enb} and h_{ob} are the eNodeB antenna height and the on-board transmitter antenna height respectively in metres, d is the propagation distance in kilometres, C is a constant correction factor, which is 3 dB in the urban environment and 0 dB in the suburban respectively. However, for applying the *COST231 HATA* Model, the propagation distance

must be in the range of 1 km to 20 km. When the propagation distance is shorter than 1 km, the L_{PL} will be,

$$L_{PL}(d)[\text{dBm}] = 10\gamma \log_{10}(d/d_0) + 20\log_{10}(4\pi d_0/\lambda) \tag{3}$$

where γ is the path loss exponent, d_0 is the reference distance, which is typically assumed as 10-100 m outdoors, λ is the carrier wavelength.

In addition to path-loss, shadowing effects could also affect the radiowave propagation in a random way.

$$P_{overall}[\text{dBm}] = P_r + \sigma_{dB} \tag{4}$$

where $P_{overall}$ is the overall received signal power. To more precisely describe the propagation of radiowaves, a stochastic model is employed to describe the uncertainties caused by this phenomenon. The shadowing effects can be seen as a deviation of the path loss which statistically obeys a log-normal distribution with a varied mean value and standard deviation [40] [41],

$$P(x_{dB}) = \frac{1}{\sqrt{2\pi}\sigma_{dB}} \exp[\frac{-(x_{dB} - P_r)^2}{2\sigma_{dB}^2}] \tag{5}$$

2.3. Outage Probability

To meet the requirements of the railway control systems on a reliable wireless connection, the received power of the desired signal must always be higher than the Rx sensitivity, otherwise this signal will be assumed as outage. However, owing to the random variable γ_{dB} caused by shadowing, unless making use of a complex ray-tracing method by conducting extensive computations, it will not be possible to exactly predict the received power of the desired signal. However, as the shadowing follows log-normal distribution, we can use a probability to ascertain when outage will occur in a wireless connection. This probability is referred to as outage probability. The outage probability is expressed as [42]:

$$P_{out} = P_r[L_{PL} > F] \tag{6}$$

where F is the fade margin, which is expressed as

$$F = P_t - L_{PL} - R \tag{7}$$

where P_t is the transmitted power in dB, R is the Rx sensitivity. Therefore, we have

$$\begin{aligned} P_r(x_{dB} > F) &= \frac{1}{\sqrt{2\pi}\sigma}\int_F^{\infty} e^{-\frac{x_{dB}^2}{2\sigma^2}}\,dx_{dB} \\ P_r(\frac{F}{\sigma} = t) &= \frac{1}{\sqrt{2\pi}}\int_F^{\infty} e^{-\frac{t^2}{2}}\,dt \\ &= \Phi(\frac{F}{\sigma}) = \frac{1}{2}\,\mathrm{erfc}(\frac{F}{\sqrt{2}\sigma}) \end{aligned} \tag{8}$$

where,

$$\begin{aligned} \Phi(x) &= \frac{1}{\sqrt{2\pi}}\int_x^{\infty} e^{-\frac{t^2}{2}}\,dx_{dB} \\ \mathrm{erfc}(x) &= \frac{2}{\sqrt{\pi}}\int_x^{\infty} e^{-t^2}\,dt \end{aligned} \tag{9}$$

In a more general scenario, due to the working channel frequency fully or partially overlapping with another nearby transmission, the calculation of the outage probability should take the interference into account. In the interest of computational efficiency in the presence of multiple interferers, in this paper, Chan's method [43] is employed to compute the outage probability. With n interferers and the corresponding power excess $(\tau_1, \tau_2, \ldots, \tau_n)$, Chan proposes an equivalent interfering signal τ_{eq} given by:

$$\begin{aligned} \tau_{eq} &= -10 \times \log_{10}(\sum_{i=1}^{n} 10^{\frac{-\tau_i}{10}}) \\ \tau_i &= m - (m_i + r) \end{aligned} \tag{10}$$

where τ_i is the power excess of the *i-th* interferer, m_i is the average power of the *i-th* interferer at the receiver; r is the system minimally accepted SIR in dBm, which is also known as the system protection ratio. Therefore, the outage probability in the presence of n interferers is

$$P_{out} = \frac{1}{2}\,\mathrm{erfc}[\tau_{eq}/2\sigma_{eq}] \tag{11}$$

where σ_{eq} equals the σ_{dBm} of the desired signal.

2.4. Transmission Delay

The main advantage of radio-based train control systems is achieved by utilizing continuous train-to-wayside wireless data message transmissions. A

detailed message flow in ETCS-2&3 is shown in Figure 2. Before requesting and receiving a MA, 6 ETCS messages are transmitted between the OBU and RBC in order to establish a session and report the TD to the wayside ZC. Once the RBC acknowledges the receipt of the TD, OBU will make a MA request, and in return, the RBC will send the corresponding MA to the OBU. With the received MA, the train will be able to proceed to run forward.

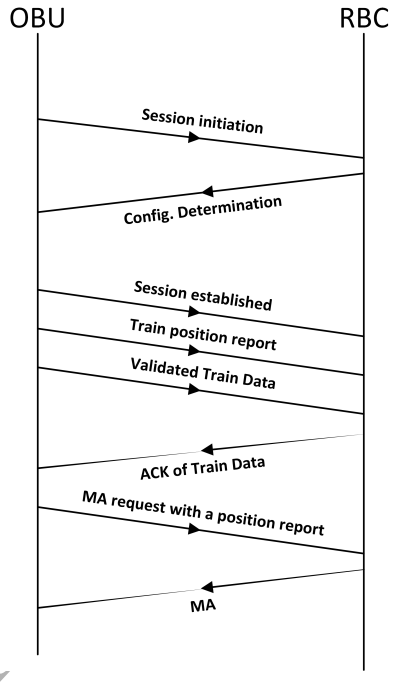

Figure 2: The message flow in ETCS [44]

However, due to the nature of the wireless communication, the data transmission quality is not guaranteed, and connection outage could happen. To ensure that the transmitted ETCS message is accurately delivered, a re-transmission mechanism is applied. This mechanism is illustrated in Figure 3. When an ETCS message is transmitted, an associated timer is triggered. For every ETCS message, an ACK is expected by the transmitter within a timeout period. If an ACK is not received in time, a re-transmission will be arranged. The commu-

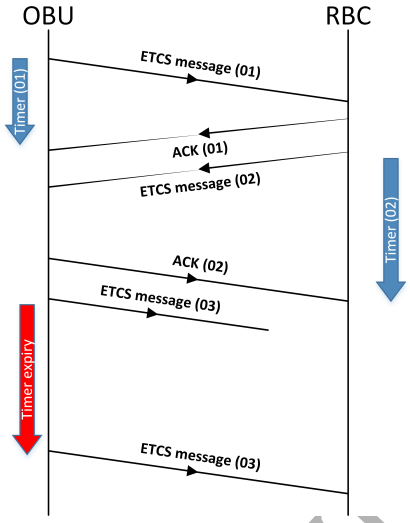

Figure 3: The message re-transmission scheme in ETCS [44]

nication delay caused in receiving a MA is expressed as [34]:

$$T_{MA} = n \times T_{timeout} + T_{network} \tag{12}$$

where T_{MA} is the overall delay in receiving a MA; n is the number of the re-transmission attempts; $T_{timeout}$ is the delay caused by re-transmission, which is dependent on the timeout duration and the number of re-transmission attempts; $T_{network}$ is the delay in a successful transmission, which is mainly dependent on the channel data rate, equipment reaction time, the size of the transmitted message and the signal propagation time between the transceivers.

Although this end-to-end re-transmission mechanism can protect the train-to-wayside communication from packet dropout, too frequent attempts of re-transmission could result in a serious communication delay, and if the overall delay exceeds the accepted maximum threshold, an emergency braking will be applied to the train. In ETCS, to assure the railway is safely operated, a strict overall delay threshold is applied.

2.5. Channel Quality

The channel quality is very important for the reliable operation of a railway system. In a wireless network, there are two metrics used to assess the channel quality, namely bit error rate (BER) and signal-to-noise-plus-interference-ratio (SNIR). Each ETCS message consists of a number of bits; when any of these bits is corrupted, a bit error will be generated. For a QPSK modulated LTE system, the BER is expressed as,

$$P_{BER} = Q(\sqrt{2 \times \frac{E_b}{(I_0 + N_0)}}) \tag{13}$$

where

$$Q(x) = \frac{1}{2}\,\mathrm{erfc}(\frac{x}{\sqrt{2}}) \tag{14}$$

where $E_b/(N_0 + I_0)$ is the energy per bit to noise plus co-channel interference power spectral density ratio. In radio-based train control systems, the maximum accepted BER must be carefully defined. Apart from BER, another important metric for a reliable wireless connection is the SNIR, which is illustrated as,

$$\mathrm{SNIR[dBm]} = 10\log_{10}(\frac{E_b}{N_0 + I_0}) + 10\log_{10}(\frac{f_b}{B}) \tag{15}$$

where f_b is the channel data rate, and B is the channel bandwidth. For a wireless network, the minimum accepted SNIR is known as the protection ratio. If the SNIR is lower than this ratio, the wireless connection is assumed as an outage.

3. Network Migration Methodology

When planning the network, as the network specifications are very different, the original BS deployment in GSM-R could be either too dense or spare for LTE-R, which will result in an unreliable data transmission. In order to achieve a well-planned network migration, in this section, a dedicated network migration methodology is proposed.

3.1. System Modelling

Along the track, it is assumed that there are h dual-mode BS used in a GSM-R network, namely $B_1, B_2, \ldots, B_h$. To render the problem tractable in migrating the network, we propose to discretize the track between two adjacent BS into a number of subsections. At the joint between two adjacent subsections an ENodeB can potentially be placed. The subsection spacing depends on the correlation length of shadowing fading [21]. To formulate the network migration problem, binary integers are used to represent whether there is an ENodeB placed or not, and whether there is a dual-mode BS upgraded to an ENodeB or not. For a track with $H-1$ subsections between adjacent BS, the problem is formulated as:

$$\begin{cases} P_\alpha = 1/0, & \alpha \in B_1, \ldots, B_h \\ P_\beta = 1/0, & \beta \in E_1, \ldots, E_{H-1} \end{cases} \tag{16}$$

where α is the BS label, β is the joint label; P_α and P_β is the decision variable for the BS and joints respectively. After the network migration, the deployment of ENodeB N is expressed as a $H \times h$ matrix,

$$N = \begin{bmatrix} P_{B_1} & P_{B_2} & \cdots & P_{B_h} \\ P^1_{E_1} & P^2_{E_1} & \cdots & P^h_{E_1} \\ P^1_{E_2} & P^2_{E_2} & \cdots & P^h_{E_2} \\ \vdots & \vdots & \vdots & \vdots \\ P^1_{E_{H-1}} & P^2_{E_{H-1}} & \cdots & P^h_{E_{H-1}} \end{bmatrix} \tag{17}$$

It follows that around $2^{H \times h}$ network migration deployment scenarios exist. The set of all these deployment scenarios is denoted as θ.

3.2. Problem Formulation

The way of formulating the ENodeB deployment has been illustrated in 3.1. The aim of the network migration is to find a deployment that ensures a reliable DCS performance in LTE-R and minimize the migration cost. To respond to this demand, in this paper, the network migration problem is formulated as:

$$\min \ F(P_{out\_max}(N), P_{out\_mean}(N), C(N)) \tag{18}$$

where P_{out_mean}, $P_{out\_max}(x)$ and $C(N)$ are the objective functions, which are the mean value value of the outage probability $\times 10^4$ and the max value of the outage probability the mean value of the outage probability $\times 10^3$ respectively. $C(N)$ is the network migration cost,

$$C(N) = K \times N \tag{19}$$

where $K = [1, k_1, k_2, \ldots, k_{H-1}]$, k is dependent on the ratio between building a new ENodeB and upgrade cost of an existing dual-mode BS.

It is worth noting that not all of the ENodeB deployments are feasible. In our prior researches [21] and [20], a method to assess the feasibility has been built. For a feasible ENodeB deployment, it must satisfy

$$\begin{cases} P_{out\_i}(N) \leq R_{outage} \\ P_{out\_i}(\dot{N}) \leq R_{outage} \\ \quad \text{s. t.} \quad i \in 1, \ldots, I \end{cases} \tag{20}$$

where P_{out_i} is the outage probability at sampling point i, I is the total number of sampling points, R_{outage} is the system outage probability threshold. In addition, to ensure that the system is still reliable in case of an AP failure, the outage probability threshold should still be satisfied by $\dot{N}$, which is the AP deployment N with a faulty ENodeB. All the feasible AP deployments form S.

Therefore, the aim of the wireless network migration in DCS is to find the ENodeB deployment $\tilde{N}$ that can minimises all the objectives shown in equation (18) simultaneously,

$$\tilde{\mathrm{N}} = \arg\min_{\mathrm{N} \in \mathrm{S}} F(N) \tag{21}$$

3.3. Algorithm Application

To solve the DCS planning optimisation problem in radio-based train control systems, in our prior work [21] and [20], two algorithms, namely exhaustive-search and customised multi-objective evolutionary algorithm based on decomposition (MOEA/D)[45], were applied, respectively. In [20], by employing

exhaustive-search and experience-based weight factors, a good optimisation performance has been achieved in a small-scale case study. However, when the system scale expands, a number of concerns will arise, in terms of computational feasibility and inaccurate results caused by adopting improper weight factors.

In stead of adopting exhaustive-search and predefined weight factors, a customised MOEA/D was utilised for solving the AP deployment optimisation problem, which produced a dedicated optimisation result based on different trade-offs in [20]. The main motivation behind the MOEA/D is to decompose the optimisation problem into a number of subproblems by associating uniformly spread weight vectors. By measuring the Euclidean distance between each of the each weight vectors, the neighborhood of each subproblem is defined. To update the neighborhood, in each iteration, the members of the neighborhood will be replaced by the newly generated solutions with the lower deposition cost g. For the $i-th$ objective function of the $t-th$ subproblem, the deposition cost g is,

$$g(x|\lambda^t, z) = \max\{\lambda_i^t|f_i(x) - z_i|\} \tag{22}$$

where λ^t is the uniformly spread weight vector for the $t-th$ subproblem, z is the reference vector, $f_i(x)$ is the $i-th$ objective function of the $t-th$ subproblem. The algorithm working flow is briefly introduced in **Algorithm 1**.

3.4. Decision Making

Due to the nature of multiple objective optimization programming, it is almost impossible to find a solution that can optimize all the objectives simultaneously. By using the customised MOEA/D, a number of Pareto optimal solutions can be found [46]. However, as there is no domination among these solutions, there is no overall optimal unless a pre-specific trade-off is defined. If the network migration wants to achieve a maximum DCS performance, the optimisation result with the lowest mean outage probability will be the optimal, however, if the network migration cares more about reducing the cost, the number of the reused dual-mode BS will be maximised. In this paper, we define

Algorithm 1

```
EP = [ ]
(λ^1, ..., λ^M)^T                          ▷ M is the sub-problems no.
B(w) = (w_1, ..., w_T)^T                   ▷ T is the neighborhood size
N_1, ..., N_M.                             ▷ N is the solutions
CF(N) = F(N)                               ▷ CF is the cost
z = (z_1, z_2, z_3)^T
for it = 1, 2, ..., n do                   ▷ it the iteration times
    for t = 1, 2, ..., M do
        N_l ⊗ N_k = N'_t, where k, l ∈ B(w),
        for j ∈ B(w) do
            if g(N'_t|λ^j, z) ≤ g(N_j|λ^j, z) then
                N_j = N'_t
                CF(N_j) = CF(N'_t)
            end if
        end for
    end for
    Update EP
end for
return EP
```

the optimal solution as the one that has an optimsed DCS performance and a minimised migration cost.

4. Methodology Application

In this section, a methodology application is addressed. Firstly, the railway environment and the network requirements in DCS are configured. Then, the conventional experience-based network planning method is introduced. Finally, an application of the optimised methodology proposed in this paper is carried out.

4.1. Railway Environment and Network Requirements

To demonstrate the idea of network migration in railways, an indicative track geometry is shown in Figure 4, including a 6 km straight part and 2π km curved part. It is assumed that this track is in a suburban area. The dual-mode BS are placed as shown in Figure 4, the separations are consistent with the reported usual BS intervals in GSM-R networks [14].

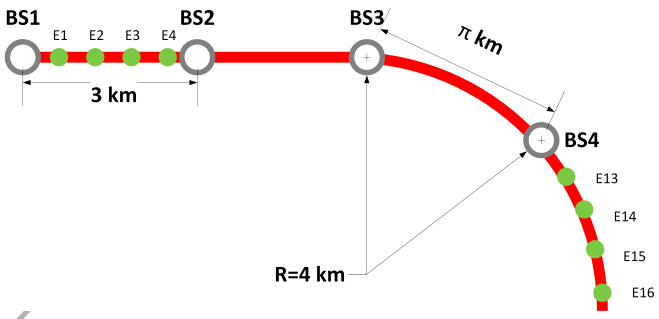

Figure 4: A track geometry of mainline railway

The whole track is divided into 4 sections by the placed dual-mode BS. We assume the correlation length of shadowing is around 600 m. Therefore, in each section, there are 4 points evenly spaced on the track marked by a green dot; at each of these points and eNodeB can potentially be placed. As a result, the

network deployment is presented as:

$$N = \begin{bmatrix} P_{BS1}, & P_{BS2}, & P_{BS3}, & P_{BS4} \\ P_{E1}, & P_{E5}, & P_{E9}, & P_{E13} \\ P_{E2}, & P_{E6}, & P_{E10}, & P_{E14} \\ P_{E3}, & P_{E7}, & P_{E11}, & P_{E15} \\ P_{E4}, & P_{E8}, & P_{E12}, & P_{E16} \end{bmatrix} \tag{23}$$

As a safety critical system, the wireless network in the ETCS has very strict requirements on the QoS. The key network requirements and the related parameters used in the wireless transmission in ETCS are shown in Table 2. To ensure that the wireless connection is reliable, the outage probability must be maintained under a threshold along the whole track, which is dependent on the maximum accepter message re-transmission attempts and the maximum accepted data loss rate. It is assumed in a communication session, the $T_{network}$ is negligible in the LTE network, and each message has the same opportunity to be corrupted. By making use of the parameters proposed in Table 2 and equation (12), we can derive that the maximum number of accepter message re-transmission attempts is 3, therefore, we can get,

$$P_{out}^3 \times (1 - P_{out}) \leq 10^{-4} \tag{24}$$

By solving inequality (24), P_{out} is obtained as around 5%. For the SIR protection ratio r, by using equation (13), equation (15) and the relevant parameters shown in Table 2, the protection ration can be derived, which is 4 dB.

4.2. Experience-based Planning Methodology

Conventionally, the idea of planning the GSM-R network is to estimate the cell range $2R$ and properly overlap these cell ranges as shown in Figure 5.

To ensure the data communication is always reliable, the cells use a mode called single network cross-site with redundant coverage [47], which means in Figure 5 the train should be able to stay in connection with a cell when the nearest cell does not work. Therefore, the cells separation distance is R. To

Table 2: Network Parameters

Parameter	Value	Parameter	Value
Timeout Interval	400 ms	Maximum MA Delay	$\leq$ 12 s
End-to-end Delay	$\leq$ 1.5 s	End-to-end Mean Delay	$\leq$ 0.5 s
Data Loss Prob.	$\leq 10^{-4}$	Data Corruption Prob.	10^{-6}
Carrier Frequency	1.8 GHz	Bandwidth	5 MHz
Sensitivity	-95 dBm	eBodeB Output Power	50 dBm
TD Packet Size	1 KB	UE Output Power	33 dBm
eNodeB Height	40 m	UE Height	4 m
eNodeB Gain	15 dBi	UE Gain	6 dBi
Data Rate	2.4 Mb/s	Path-loss Exp.	2.5
Shadowing Variable	2.6 dB	Modulation	QPSK
Access scheme	OFDMA	Fade Margin	10 dB
Cable Loss	1 dB	Internal Operation Delay	2.5 s
Reference Distance	100 m		
Outage Probability	$\leq$ 5%	Protection Ration	4 dB

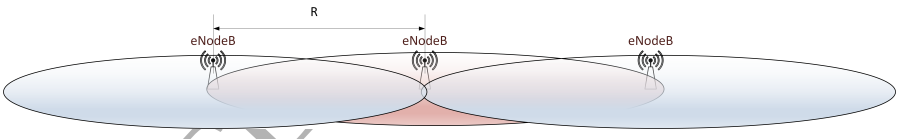

Figure 5: The cell range of in a typical communication-based train control system

take the shadowing effects into account, a fade margin is used to mitigate the impact on the cell range estimation. The cell separation distance R is set as the distance, where the received signal power P_r equals the Rx sensitivity.

$$P_r(R) = \text{Rx} \tag{25}$$

By using equations (1) and (2), the cell separation distance R can be derived, which is around 2.7 km. Therefore, for the track shown in Figure 4, 5 LTE-enabled BS are required.

4.3. The Optimisation Result

To apply the proposed methodology in Section 3, in this part, an indicative case study is presented. The relevant simulation parameters are listed in Table 3.

Table 3: Optimisation Parameters

Parameter	Value	Parameter	Value
Sampling Interval	50 m	k-factor	5
Population Size	20000	Neighborhood Size	2000
Iteration	50	Channel No.	2

In this case study, the k-factor is set as 5, which means that the cost of building a LTE-based BS is five times more than upgrading an existing dual-mode BS. The optimisation result is shown in Table 4. From the result we

Table 4: Network Migration Result

N	Deployment	P_{out_max}	P_{out_mean}	CF	BS No.
1	4,9,16	0.3109	0.0258	12	3
2	3,6,16	9.5249	0.8423	7	3
3	3,6,11	3.7762	3.2253	7	3
4				25	5

can see that there are 3 Pareto Optimal (PO) deployments, namely N_1,N_2 and N_3, which means that there is no domination between these deployments. The deployments are shown in equation (26) The migration cost of the conventional planning is shown in N_4. N_1 has the best data exchange performance, however, the migration cost is quite high; N_2 and N_3 have the minimised migration cost, but have a worse wireless communication performance than N_1; the conventional planning N_4 has the highest migration cost. To evaluate the wireless communication performance of these deployments and confirm which deploy-

ment is the optimal, in the next section, DCS performance simulations of each deployment will be carried out.

$$N_1 = \begin{bmatrix} 0, & 0, & 0, & 1 \\ 0, & 0, & 0, & 0 \\ 0, & 0, & 0, & 0 \\ 1, & 1, & 0, & 0 \\ 0, & 0, & 0, & 0 \end{bmatrix}, N_2 = \begin{bmatrix} 0, & 1, & 1, & 0 \\ 0, & 0, & 0, & 0 \\ 1, & 0, & 0, & 0 \\ 0, & 0, & 0, & 0 \\ 0, & 0, & 0, & 0 \end{bmatrix}, N_3 = \begin{bmatrix} 0, & 1, & 0, & 1 \\ 0, & 0, & 0, & 0 \\ 1, & 0, & 0, & 0 \\ 0, & 0, & 0, & 0 \\ 0, & 0, & 0, & 0 \end{bmatrix} \quad (26)$$

5. Result Evaluation

In section 4, three optimised dual-mode BS deployments are addressed. To evaluate the performance of the wireless network in a cost-effective way, simulation is required [48]. In this section, to ensure this deployment can fulfil the ETCS network requirements, the DCS performance evaluation of these optimised dual-mode BS deployment are implemented in an integrated simulation platform [49].

5.1. Simulation platform

This integrated simulation platform is formed by two parts, one is a railway simulator, and the other is the network simulator OMNeT++ [50].

The railway simulator is a microscopic railway traffic simulator, developed by the Birmingham Centre for Railway Research and Education (BCRRE) at the University of Birmingham. It has a number of panels, including traffic, timetable, train run, train type, vehicle, infrastructure, station, routes, interlocking, junction, maps, models and rules. By configuring different panels, this railway simulator can generate the railway traffic and simulate the functions of a railway control system.

OMNeT++ is an open source object-oriented modular discrete network simulation environment. To accurately validate the AP deployment in DCS, we integrate OMNeT++ and the railway simulator. In this integrated simulation environment, the wireless data transmitted and received between the train and

wayside APs in the railway simulator will go through the real-world channel created in OMNeT++; meanwhile, the data transmission quality in the railway simulator is determined in OMNet++. As the OMNet++ can create a realistic physical propagation environment and make real impacts on the wireless communication quality, the simulation result is convincing.

5.2. DCS Performance Evaluation

In the simulation, all of the migration deployment scenarios addressed in Section 4 are set in the integrated simulation environment. A screenshot is displayed in Figure 6. For every testing scenario, the network setting follows the configurations in Table 2. The train is set to do shuttle runs, the total running time is 20000 seconds; and during the whole journey, 40000 TD messages are scheduled. The simulation result is shown in Table 5.

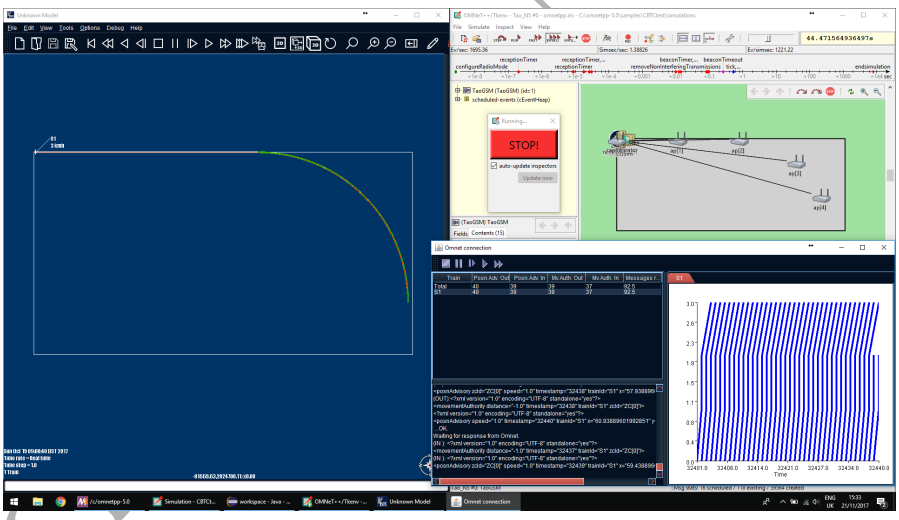

Figure 6: A screenshot of the integrated simulator

From the simulation result, we can see that all of the deployment scenarios fulfil the network requirements of ETCS [34], in terms of the data-loss rate and the maximum end-to-end packet delay, which means all the deployments can

be adopted in ECTS systems and achieve a reliable train-to-wayside wireless communication performance. As deployment N_3 has the best performance in the end-to-end packet delay and has a minimised migration cost, this deployment is the optimal deployment.

Table 5: Network Simulation Result

N	TD Receipt	Delay:Mean (ms)	Delay:Max (ms)	CF
1	100%	0.969	10.3	12
2	100%	0.929	6.6	7
3	100%	0.926	5.8	7
4	100%	0.935	6.6	25

6. Conclusion

The DCS is the core part of the radio-based train control systems, which rely a well-planned wayside BS deployment. In this paper, a novel network migration methodology eligible in radio-based train control systems is proposed. By using this methodology, a dual-mode BS deployment with good wireless communication performance and high cost-effectiveness is achieved. In order to get an accurate network planning, the characteristics of railway systems, including a typical railway environment topography and strict requirements on the wireless communication dependability, have been carefully taken into consideration. To render the problem tractable, we discretize the track into a number of sections, and at the edge points of each section, binary integer decision variables are used to formulate the migration problem. To precisely and efficiently search the optimisation result, the customised MOEA/D is adopted, which has been proved to have a good performance in network deployment planning in our prior work. In the simulation result, it shows that the deployment which has the minimised migration cost and the best performance in end-to-end packet delay is the optimal migration scenario. The proposed methodology is also generic for other

systems, for example, when upgrade to the 5G cellular networks, this network migration method can be customised and adapted.

However, in this paper, only a low LTE-R frequency migration scenario is considered (1.8 GHz). In order to achieve a higher channel capacity, in some migrations, high-frequency based LTE-R technology could be adopted, which will result in a short cell-range and lead to a dense BS deployment; in some cases, the communication resource can be reduced by using event-triggered scheme [51], which is a common problem in microgrid [52]. In our future work, all the mentioned lack will be further investigated; moreover, as just an indicative case study is carried out on a small-scale network migration work, to conduct the network migration in real-world systems, a more efficient optimisation searching, such as parallel Processing algorithm based cloud computing [53], will be considered in our future research.

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